Detectors for Visible and IR Interferometry

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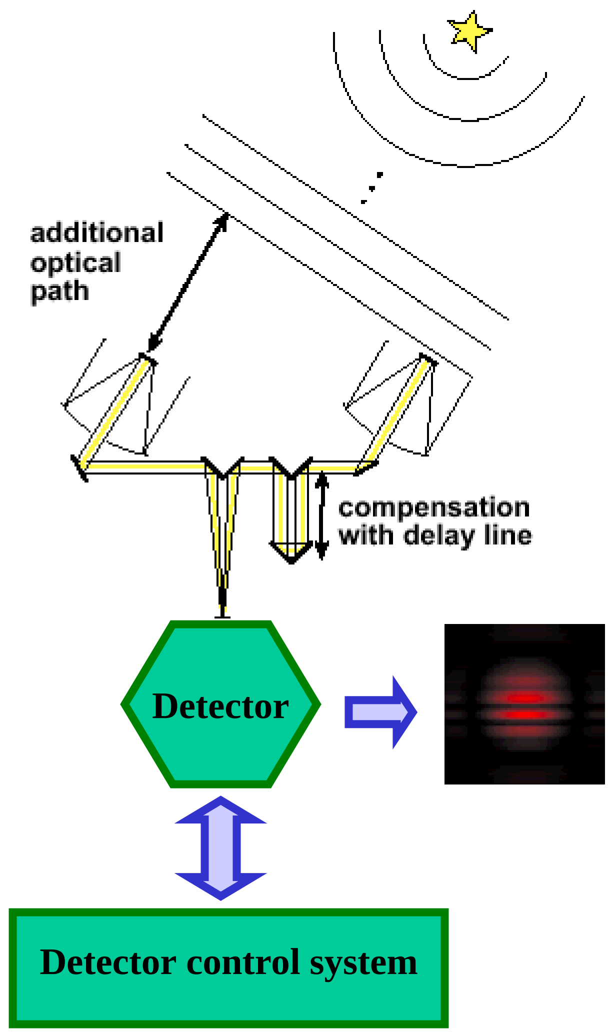
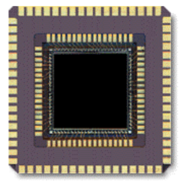
Anatomy of a Typical System

- Beams are collected by telescopes
- Transported & delayed by optics
- Combined, in some way
- Some form of interference pattern results
- Detector senses the light modulation
- Electronics records detector output
- Electronics synchronizes this process with other subsystems
- Data storage, reduction, modeling
- Send results to OLBIN
- Write a paper

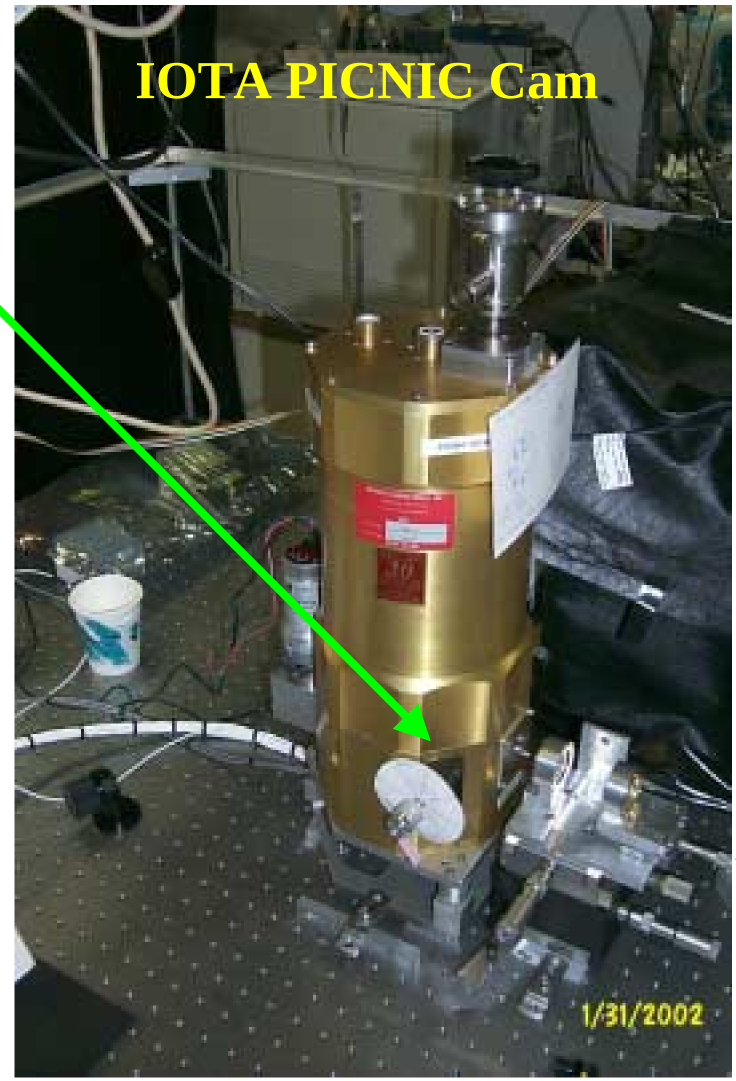


The Finished Detection Product … An Example

Detector is deep inside cryostat, in contact with coolant (LN2 in this case)



For low noise operation, great care must be taken in design & implementation of readout electronics



Computer

Digital Data Out

AMP

ADC

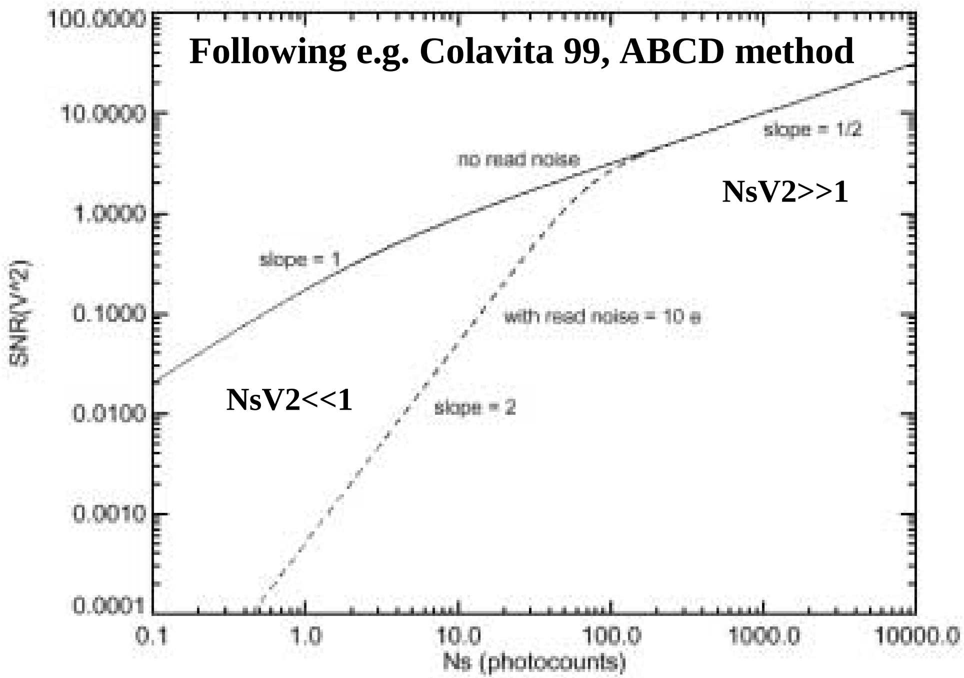
Analog Data OUT

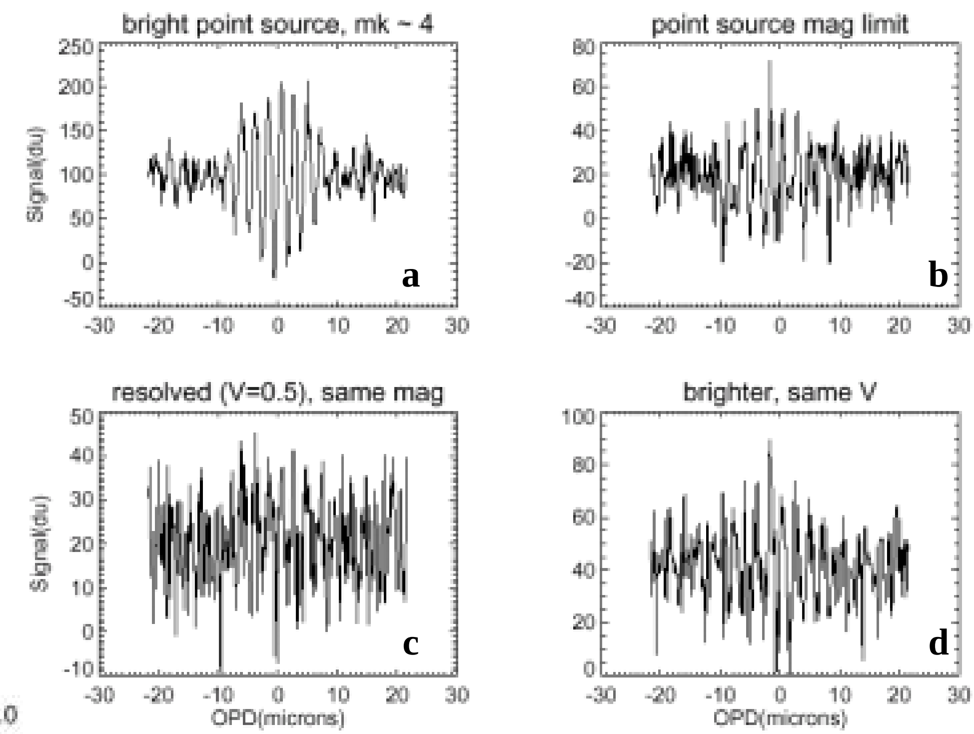
Combined Light IN

Power
Bias
(Clocking)

Signal and Noise

- Details of SNR(V,ϕ) depend on the particular arrangement
- But it is always good to have lots of signal (Ns,V) and low detector noise  (duh!)



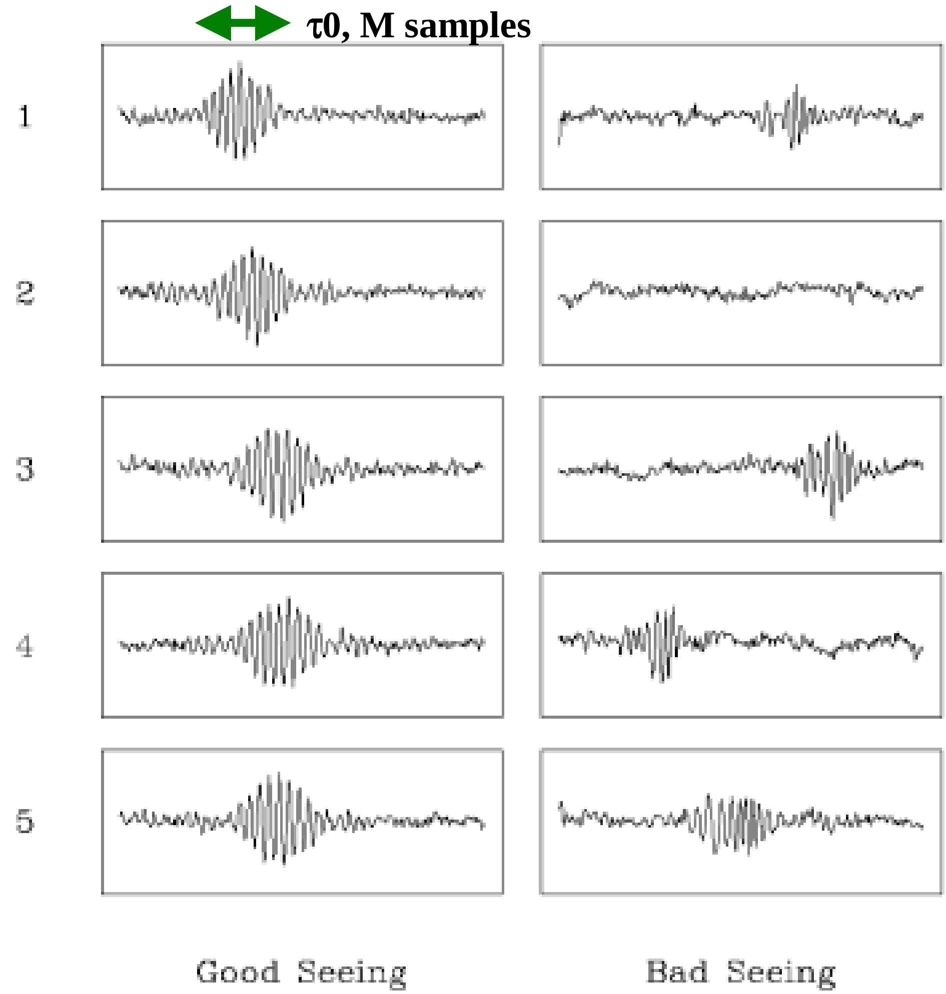


Limitations on the Coherent Signal: the Atmosphere

- Telescope size ~ r0
  (10-50 cm, for Vis-NIR)
- Detection time ~ τ0
  (10-50 ms, for Vis-NIR)
- Must have enough photons in coherence volume: $\pi \cdot r_0^2 \cdot \tau_0 / 4$

Those are severe limitations:

- No huge light bucket
- No deep integrations (Δt=τ0/M)
- Sensitivity & Calibration are affected

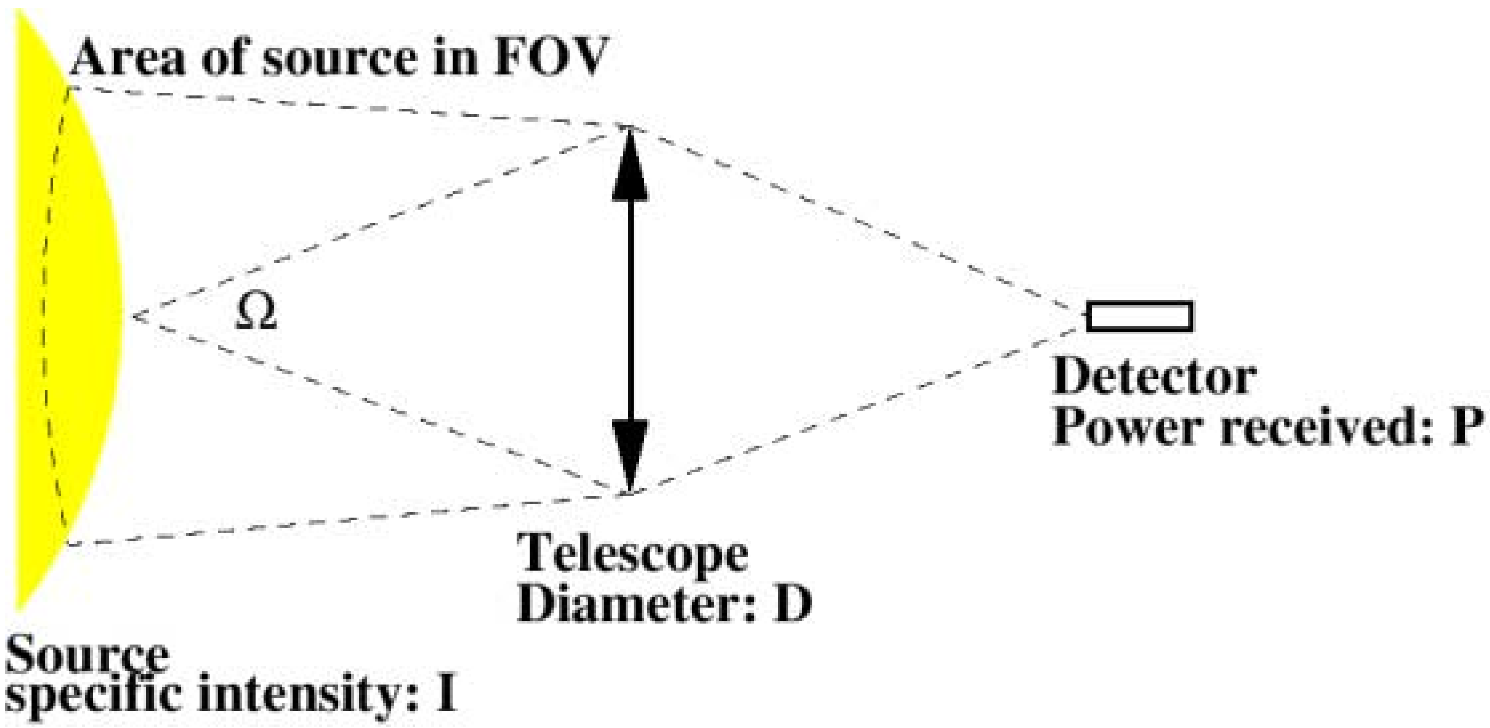


⇒ High premium in low detector noise

Can Coherence Time and Area be “Increased”?

- Adaptive optics: ideally, effectively $r0 \rightarrow D$
- Phase referencing: ideally, effectively $\tau 0 \rightarrow \infty$
- Examples: I-Keck, VLTI
- see lectures by A. Quirrenbach and W. Tango

Signal Captured by Each Telescope



$$P_\lambda[W \cdot m^{-1}] = I_\lambda[W.m^{-2}.str^{-1} \cdot m^{-1}] \cdot A_{\substack{source \\ in\, FOV}} \cdot \Omega_{\substack{telescope \\ viewed \\ from\ source}} \cdot T_\lambda$$

T: overall transmittance

Source usually unresolved by individual telescopes

Good Photons, Bad Photons and Noise

Source:

$$Ns[photons] \approx F^0_{\lambda 0}[W.m^{-2}.\mu m^{-1}] \cdot 10^{-0.4 m_\lambda} \cdot A_D \cdot \Delta t \cdot \Delta\lambda \cdot \frac{\lambda_0}{hc} \cdot T_{\lambda 0}$$

Background:

$$N_B[photons] \approx B(\lambda, T) \cdot A_D \cdot FOV^2 \cdot \Delta t \cdot \Delta\lambda \cdot \frac{\lambda_0}{hc} \cdot (1 - T_{\lambda 0})$$

$$\text{note that}: (A_D \cdot FOV^2)_{\min} = \frac{\pi}{4} D^2 \cdot (1.22\frac{\lambda}{D})^2 = 1.2\lambda^2$$

Total noise (neglecting wave correction to photon shot noise – see next slide -):

$$Noise[e, rms] = \sigma = [N^e_S + N^e_B + (N^e_{dark} + R^2)]^{1/2}$$

with:

$$N[electrons] = N[photons] \cdot \eta$$

η: quantum efficiency
Δt: integration time
Δλ: spectral bandwidth
λ0: center wavelength
B: Planck function
R: electrons rms read noise

Aside: Photon Noise

- The full Bose-Einstein statistics of photons includes correlations between photon arrivals due to their wave nature, the full expression for the noise variance is then:

$$\sigma^2 = N \cdot \left[1 + \frac{\varepsilon T \eta}{e^{h\nu / KT_S} - 1} \right]$$

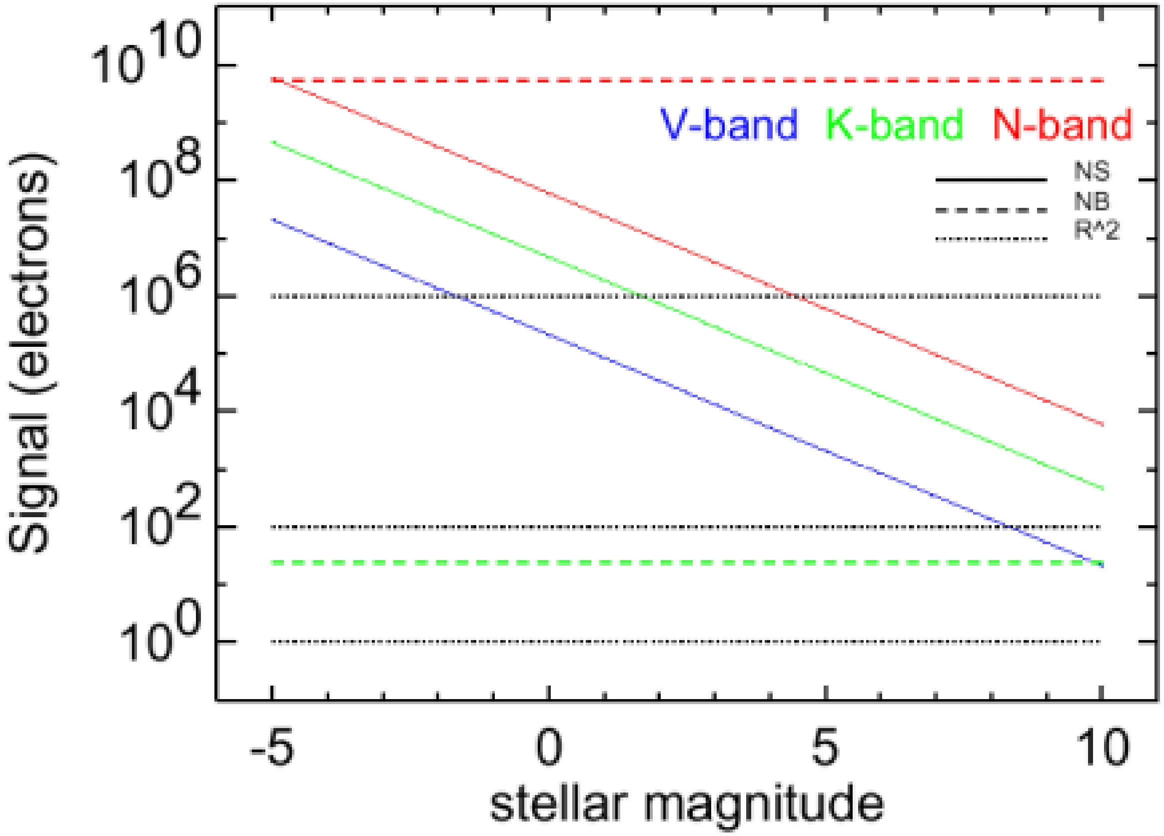
N: mean # photons

ε: source emissivity

Ts: source temperature

- If hν >> KT (Wien regime): σ2 = N (familiar shot noise expression)
- If hν << KT (Rayleigh-Jeans): σ2 = N[1+εTηKTs/hν] (wave noise)
- Otherwise, must use full expression
- Note: even if not in Wien regime, correction factor may be negligible if system transmittance (T) is small, as is often the case in VIS & IR interferometers

How Many of Each do we Get?



D = r0(λ)
Δt = τ0(λ)
V: 0.56 μm
K: 2.20 μm
N: 10.1 μm
Δλ/λ = 20%
η = 0.5
T = 0.5
TB = 270K = -3ºC
(A*Ω) = 1.2x λ^2
R = 1, 10, 1000 e rms

V-background is way off-scale

Roughly speaking:

VIS: source photon noise limited
Near-IR: detector noise limited
Mid-IR: background photon noise limited

What Detectors do we NEED?

- Not many pixels
  - (but probably too many for single-element detectors)
  - say: ≤ 7 telescopes, ≤ 21 baselines => ~ 50 pixels
  - plus spectral resolution: R ~ 10 – 10000

⇨ probably 100^2 pixels at most, not 1000^2 pixels

- Fast frame rates: whole "frame", or part of it, read every $\tau 0$
- Low noise, even in Mid-IR
- Sub-windows with independent frame rates

  (e.g. phase referencing channels + science channels)

Detectors Types by Transducer Mechanism

- Photon detector [X-Ray, UV, VIS,IR]

  Respond directly to individual photons, by releasing charge carriers, which may cause a chemical response, modulate an electric current, or move directly to an output amplifier

  - **Photographic plates**
  - **Photoconductors, intrinsic and extrinsic**
  - **Photodiodes (or photovoltaic)**
  - **Photoemissive**

- Thermal detector [X-Rays, IR, sub-mm]

  Absorb and thermalize photon energy, changing electrical properties of the material and modulating an electrical current that passes through it

- Coherent (Heterodyne) detector [IR, sub-mm, radio]

  Respond to the electric field and preserve phase information of incoming photons, by frequency down-conversion

Wavelength regimes:

Vis: 0.4 – 0.7 μm
Near IR: 1 – 2 μm
Thermal IR: > 2 μm
Submm: 350 – 1000 μm
mm, radio: > 2000 μm

What do People Like, or Use?

Facility	Visible	Near-IR	Thermal-IR
COAST	APD	NICMOS	X
GI2T	CP40,20	X	X
IOTA	CCD APD	NICMOS PICNIC	InSb
ISI	X	X	Heterodyne
NPOI	APD	NICMOS	X
PTI	X	NICMOS	X
SUSI	PMT/APD	X	X
CHARA	CCD	PICNIC	X
I-KECK	X	HAWAII	Si:As IBC
VLTI	X	PICNIC	Si:As IBC

APD: photodiode
CCD: intrinsic photoc array
PMT: photoemissive
CP40: photoemissive
NICMOS: photodiode array
PICNIC: “”
HAWAII: “”
InSb: photodiode
Heterodyne mixer: HgCdTe
extrinisic photoc
Si:As IBC: extrinsic photoc

Important Parameters

- Quantum efficiency: fraction of incident photons converted to signal
- Noise: uncertainty in output signal, ideally only due to stat photon fluctuations
- Linearity: proportionality between output and number of input photons
- Dynamic range: maximum allowed variation in signal
- Number and size of pixels
- Time-response: min time over which detector can react to photon rate changes
- Spectral-response: λ-range over which photons can be detected

These properties influence:

- Sensitivity
- Data Calibration
- Use practicalities

Relevant Physics: Semiconductors

- Key: Electrical properties dramatically altered by absorption of individual photons (unlike insulators and metals), because energy band-gaps are comparable to single photon energies
- ***Intrinsic*** process: in a crystal with complete valence bonds, an [electron,hole] pair is excited to conduction band thermally or by absorption of photon of energy ≥ energy band-gap (Eg)
- Longer wavelength response can be obtained by introducing impurities (***extrinsic***), which leave more loosely bound electrons (n-type) or holes (p-type), which can be excited into conduction band by absorbing energy ≥ excitation energy (Ei)

Intrinsic Photoconductors

- Most basic kind
- Basis of CCDs
- Illustrate many General Principles:

  externally bias the material, control thermal excitation by cooling, and measure electrical current resulting from photon-generated charge carriers (photocurrent).

  Key property (sought in all semic detectors):

  large impedance $\Rightarrow$ increases signal and reduces noise

Example intrinsic semiconductors, pure and compound:

Column	Name	Eg(eV)	λc(μm)
IV	Ge	0.67	1.85
IV	Si	1.11	1.12
III-V	InSb	0.18	6.89
II-VI	CdTe	1.58	0.78

cutoff wavelength :

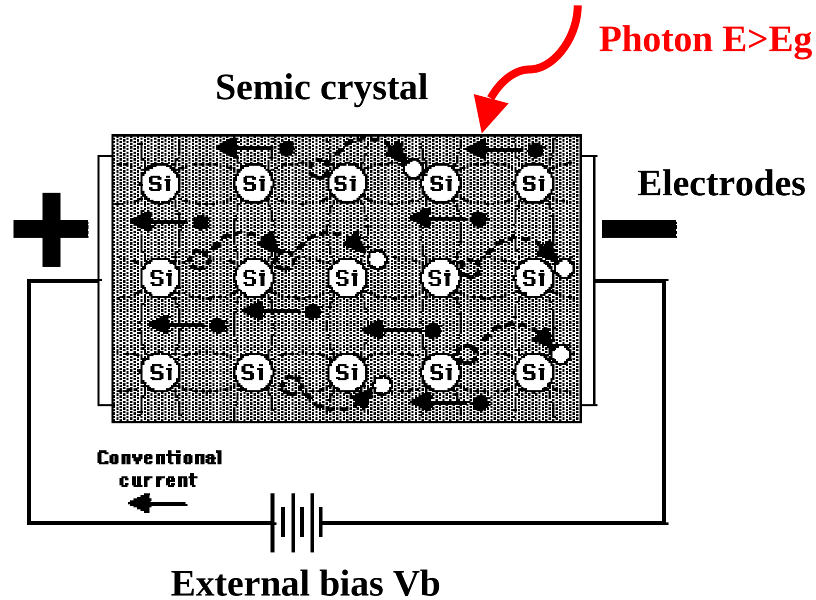
$$\lambda_C = \frac{hc}{Eg}$$

Intrinsic Photoconductors: Signal

Photocurrent:

$$I_{ph}[A] = \Phi[\,photons \cdot s^{-1}] \cdot e \cdot \eta \cdot G$$

η.G: probability that a photon produces a carrier that penetrates to an electrode



Large signal:

- Increase η (absorption coeff, absorption length)
- Increase gain G:

  decrease electrode separation (but decreases area or length)

  increase Vb (up to breakdown)

  manipulate material properties (purity, low T)

Intrinsic photoconductors: noise

A. Signal dependent noise:

- Fundamental limit: Poisson (or Bose) statistics of incoming photon stream => generation-recombination (G-R) noise

$$\text{in number}: rms = \sqrt{2N}; \text{source or background}$$

$$\text{in current}: \sigma_{I-GR}^2 = 4 \cdot e^2 \cdot \phi \cdot \eta \cdot G^2 \cdot B$$

$$\text{e.g. } B = 1/(2 \cdot \Delta t) \quad \text{is the noise bandwidth}$$

- Thermally generated carriers add their own G-R noise

  Very steep T dependence exp(-Eg/2KT)

  => needs to be constant, but for e.g. Si gone by convenient T=77K

Intrinsic photoconductors: noise

B. Noise sources in the absence of external signal:

1. Johnson (or Nyquist) noise

$$\sigma^2_{I-J} = \frac{4KTB}{R}$$

Example:
T = 300K
R = 10^7 Ohm
B = 500Hz, Δt = 1ms
rms: ~ 9x10^-13 A
~ 5600 electrons

2. Reset or KTC noise
   (uncertainty in integrated charge)

$$\sigma^2_Q = KTC$$

Example:
T = 300K
C = 10 pF
rms: ~ 2x10^-16 A
~ 1270 electrons

Both are manifestations of same phenomenon: microscopic random (Brownian) motions of charge carriers

Intrinsic photoconductors: noise

C. Additional sources usually present:

- Excess noise: 1/f

  (not well understood theoretically, but very common)

$$\sigma^2_{I-1/f} \propto \frac{B}{f^b};\ \mathrm{b} \approx 1$$

- Total noise, so far:

$$\sigma^2_{In} = \sigma^2_{I-GR} + \sigma^2_{I-J} + \sigma^2_{I-1/f}$$

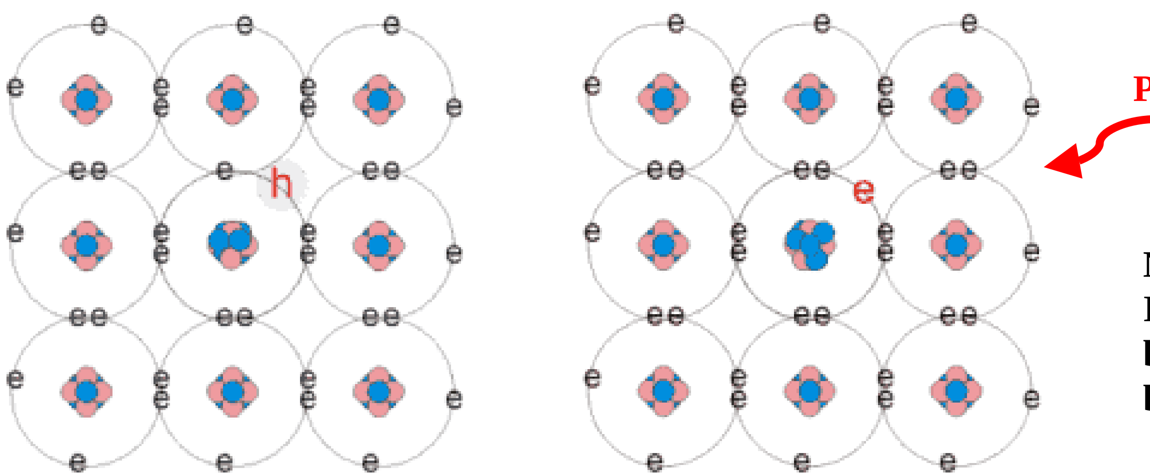
- Also add: Interference (pickup or microphonic), or eliminate electronically or in post-processing. These are, contrary to previous cases, "line processes": well defined frequencies

Intrinsic photoconductors: f-response

- Limited by:
  - RC-time: exponential with $\tau \propto RC$
    detector element + electronics
  - Dielectric relaxation: exponential with $\tau \propto 1/\Phi$
    effect more important at low light levels
    only depends on detector parameters
  - Charge carrier lifetime, τ, before recombination

Extrinsic Photoconductors

- For $\lambda > 1.8\ \mu m$, intrinsic photoconductors are not well suited
  - high quality Si & Ge have $\lambda c = 1.1, 1.8\ \mu m$
  - smaller band-gap compounds do not have high impedance
  - materials have problems of uniformity, stability, contacts …
- Solution: add impurities => conductivity is induced by exciting impurity carriers, which requires smaller excitation energy (Ei)



p-type n-type

Photon E>Ei

Note:
Intrinsic process must be suppressed using blocking filters

Extrinsic photoconductors

- Notation: semic:majority dopant (e.g. Si:As)
- Low Ei => easy to excite thermally => low T
- Absorption coeff ~1000x smaller, limited by impurity concentration

  => must have high volume (~1mm) to get good η (but increases probability of spurious signal)
- Noise: same processes as with intrinsic photoc

Examples:

	Majority atoms	
Impurity atoms	**Ge λc(um)**	**Si λc(um)**
B	**119**	**28**
In	**111**	**7.9**
As	**98**	**23**
Sb	**129**	**29**

Extrinsic photoconductor: selected variants

- Impurity Band Conduction (IBC) a.k.a Blocked Impurity Band (BIB)
  - Key: Optimize optical and electrical properties separately
  - Layer with high impurity concentration for high η
  - Blocking layer (BL) of high purity for high impedance
  - $\sqrt{2}$ noise improvement, due to low impedance of absorbing layer
  - controlled gain G > 1, typically 5-10, but noisy process (because BL is not sharply defined)
- Example:

  VLTI MIDI detector for 10-20 μm

  Si:As, 320x240 pixels

  η=40%, 1000 electron read-noise

Extrinsic photoconductor: selected variants

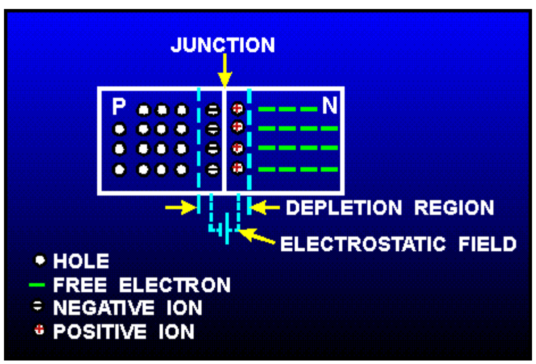
- Solid State Photomultiplier (SSPM)
  - Key: IBC with extra layer optimized for gain
  - spectral response similar to Si:As IBC, but
  - 1 photon produces avalanche of ~ 10^4 electrons
    => pulse easily distinguished from electronic noise
  - pulse width few nsec, broadened by electronics to few μsec
  - dead time ~ 1 μsec per count (causes non-linearity)
  - dark pulse rate ≤ 1000 e/sec, at T = 6 – 10K
  - but low T also lowers η (usually 1-50%)
  - SNR(SSPM) > SNR(non-photon counting) for B>100Hz
  - require careful control of bias and T!
  - area of needed improvement: η

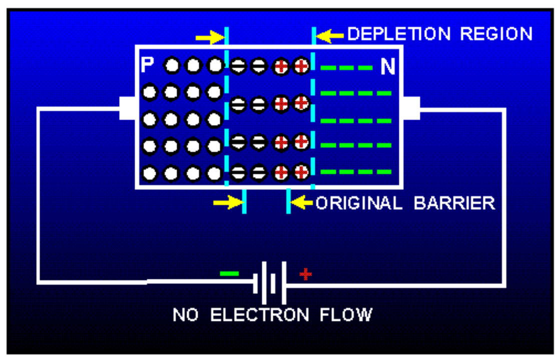
Photodiodes a.k.a Photovoltaic Detectors

- Photodiode = junction between 2 oppositely doped regions
- Key: depletion region with E-field
- Achieves simultaneously high G ~ 1 and R, for λ = 1-5 μm materials
- Detector of choice in that spectral region
- Basis of NIR arrays (e.g. NICMOS,PICNIC,HAWAII,SBRC)

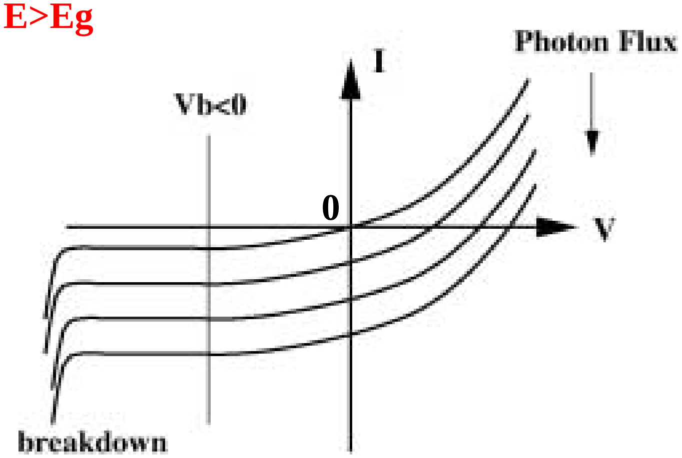
Note: Photo-absorption is via intrinsic process

Photon E>Eg





reverse bias (Vb)



Photodiodes

- As shown in I-V curve:
  - I $\propto$ photon flux, for constant Vb<0
  - if Vb varies, ~ 10-20% smooth non-linearity (e.g. NICMOS etc)
  - near Vb=0, no more response: saturation (e.g. NICMOS etc)
- Also have $\sqrt{2}$ advantage in G-R (shot) noise
- Example materials: InSb (λc=6.8μm), HgCdTe (variable λc<15μm)
- Diode => high capacitance, which limits t-response, and noise
- C & R $\propto$ impurity concentration

  => desired low C and high R require a compromise
- **Example:**

  InSb photodiode
  R = 10^11 Ohm, T = 50 K, B = 500 Hz, Δt = 1 ms
  rms noise current (Johnson only): 4x10^-15 A
  rms noise electrons: 23

Photodiodes: Variants

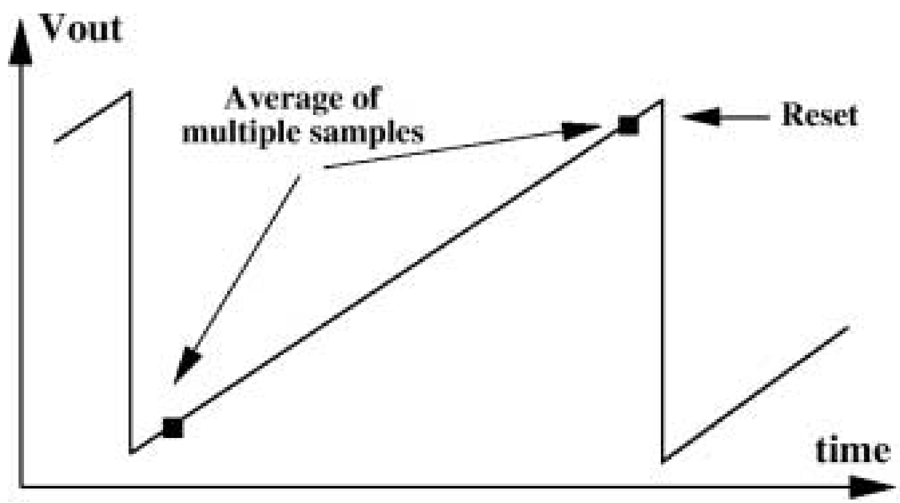
- Avalanche Photodiodes (APD)
  - Key: large rev bias, just short of breakdown
    => carrier acceleration produce avalanche in depletion region
  - similar to IBC, but require E > Eg, not Ei $\Rightarrow$ ~20x larger field
  - designed as PIN devices (I: layer of intrinsic semic) => fast
  - Si based 0.3-1.1 μm , Ge based 0.8 – 1.6 μm
  - allows counting of pulses from individual photon events
  - pulse rise times: ~ few ns, dead times: ~ few 100 ns
  - dark count < 100 sec^-1 at T ~ -40C (233K)
  - require good T control for constant gain
  - simpler, lighter, cheaper, alternative to Photomultiplier Tubes
  - coming soon: InGaAs for 0.9-1.7 μm (currently η~15%)

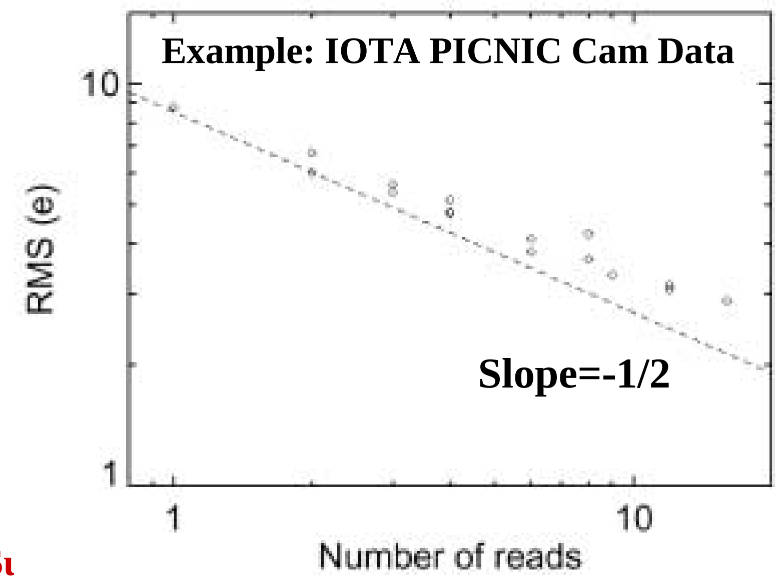
Readout Electronics

- Detector output must be processed by external electronics
- Infinitesimal currents arising in these very high impedance devices must be received and amplified by special (FET) circuits
- Of special interest:
  - Trans-impedance amplifier (TIA) [used in SSPM, photodiodes]
  - Integrating amplifiers [used in arrays e.g. CTIA, SFD circuits]
    - Constant photocurrent charges an equivalent capacitance
    - Charge accumulated Q measured as ΔVoltage at FET output
    - Usually changes diode bias during integration $\Rightarrow$ somewhat non-linear
    - Q includes dark current & FET leakage
    - Minimum noise is $\sqrt{}$ of number of charges collected
    - Additional noise sources …

Integrating amps: KTC (reset) noise $\sigma_Q^2 = \frac{KTC}{e^2}$

- Additional uncertainty (noise) in charge after reset
  - Example: C=10^-12 F, T=50K, σQ = 164 electrons!
- But, can be greatly reduced with "clever" readout methods
- Also, take advantage of non-destructive readout capability
  - signal is preserved at FET gate and can be read repeatedly
- Example ("Fowler" sampling – see ApJ 1991):





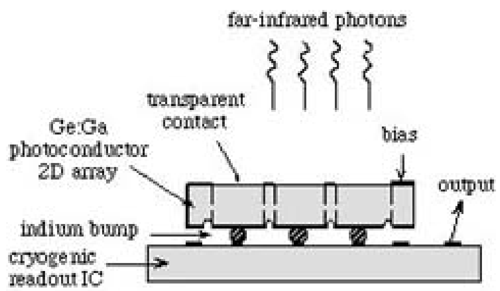
Arrays: Visible

- Array of intrinsic photoconductors + integrating caps + FET output
- Millions of high performance pixels
- Monolithic Si structure
- Collection of charge under depletion region created by electrode
- Charge transfer to common output by phasing electrode voltages

  => adds it own noise, allows charge binning
- Reach near fundamental limits for x rays – 1 μm, except when rapid t-response is required
- Dark current for ~ 150K (-123C) virtually un-measurable
- Read-noise: 1 – 5 electrons, well-depth ~ 10^6 electrons
- η = 80 – 100%

Arrays: Infrared

- Separate optimization of readout & detectors
  - readout: usually Si
  - detectors: photodiodes for 1- 6 μm
    extrinsic or IBC for 4 – 40 μm
  - more difficult fabrication process => expensive
- Multiplexer allows random access of pixels by direct addressing
- η = 60 – 90% (Near-IR), 30-80% (Mid-IR)
- Read-noise: 10 – 70 e (photodiodes), 1000-2000 e (IBCs)
- Well depth ~few 10^5
- Rapid, on-going development:
  - noise: 2000 e (1970s) → <10 e today
  - price: 2000$/pixel (1970s) → 1$/pixel today

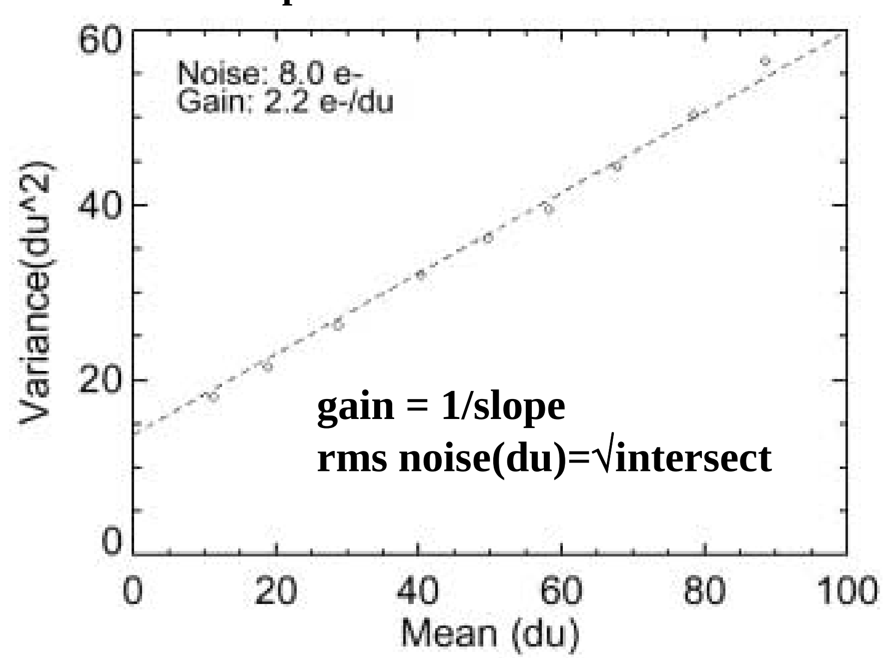


B.T.W. How Do I Measure the Read-Noise?

- Operational Definition: rms of signal out with zero signal in
  - ❖ but then must convert to e using nominal parameters
- Or measure with "Poisson stats experiment":

$$\text{gain}: g(e/du)$$
$$mean(du)\cdot g = mean(e)$$
$$\sigma(du)\cdot g = \sigma(e)$$
$$\text{assume Poisson statistics}:$$
$$\sigma(du)\cdot g = \sqrt{mean(du)\cdot g}$$
$$g = \frac{mean(du)}{\sigma^2(du)}$$

Example: IOTA PICNIC Cam Data



Coherent (Heterodyne) IR Receiver

- Interfere EM field of incoming photons with local oscillator
- Fields are mixed at a quadratic photon detector (photoconductor, photodiode, PMT, or bolometer); output $\propto$ power
- Resulting signal has *cos* term at difference freq. (IF) encodes the spectrum & retains the phase information of incoming wavefront
- Amplitude $\propto$ LO power, allows to overcome many noise sources
- Amplification of mixer output by HEMT electronics
- Outputs from different telescopes can be combined coherently to reconstruct incoming wavefront: interferometry
- Can also send IF output to bank of narrowband filters

Heterodyne: Limitations

- Bandwidth:
  - limited by f-response of mixer + electronics
  - usually: 10^6 – 10^9 Hz => < 0.01% at 10 μm!
- Throughput:
  - at high IR freqs, LO is CW laser
  - interference at beam splitter requires FOV ~ diffraction limit
  - also, only one signal polarization produces signal

    $\Rightarrow$ "single mode" detector
- See C. Townes chapter in 1999 Michelson School book, or J. D. Monnier's PhD thesis (UC Berkeley 1999), for SNR comparison with direct detection

Near Future Promising Technologies

- LLL-CCD (Marconi Applied Technologies)
  - adjustable avalanche gain 1 – 10000
  - << 1 electron read-noise
  - photon counting capability
- Next-Generation IR FPAs (Rockwell Science Center):
  - windowing capabilities
  - on-chip clocking, bias & ADC electronics
  - small format (8x8 $\rightarrow$ 128x128), fast readout, very low noise (<1e) devices (in development for AO)
- Superconducting Tunnel Junction (STJ) Detector (ESA)
  - high rate, low noise photon counting, UV $\rightarrow$ IR
  - intrinsic photon energy determination